Electron Cooling R&D

RHIC PROGRAM REVIEW

July 7, 2005

Presented on behalf of the many people who contribute to the electron cooling R&D effort by

Ilan Ben-Zvi

The objectives and challenges

- Increase RHIC luminosity: For Au-Au at 100 GeV/A by ~10
- Cool polarized p at injection
- Reduce background due to beam loss
- Allow smaller vertex

- Cooling rate slows in proportion to $\gamma^{5/2}$.
- Energy of electrons 54 MeV, well above DC accelerators, requires bunched e.
- Need exceptionally high electron bunch charge and low emittance.

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R&D issues

- Understanding the cooling physics in a new regime to reduce uncertainty
  - understanding bunched beam, recombination, IBS, disintegration
  - what is the exact form of the friction force, use direct simulations
  - cooling dynamics simulations with some precision
  - benchmarking experiments
  - stability issues
- Developing a high current, energetic, magnetized, cold electron beam. Not done before
  - Photoinjector (inc. photocathode, laser, etc.)
  - ERL, at x20 of state-of-the-art
  - Beam dynamics of high-charge magnetized beam
- A very long, super-precise solenoid (30 m long, 2 Tesla, 8×10^{-6} error) – if we used magnetized cooling.

Impact of cooling theory

- Significant progress made in theory, leading to significant changes in the cooler design, e.g. superconducting gun.
- Two alternative cooling approaches are being considered:
  - Magnetized cooling
  - Non-magnetized cooling
- Consequence: Uncertainty in beam parameters
- Consequence - Some milestones delayed:
  - Start to end simulation
  - Completion of gun
  - Superconducting solenoid prototype.

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Status of IBS before 2004, and 2004-2005 experiments

- IBS in RHIC was estimated based on average growth of all bunches.
- In cooling simulations simplified approximate formulae were used.

- Heating only from IBS.
- Measured bunch length, emittance.
- Measured bunches with various intensities and emittances.
- Detailed comparison of various theoretical models of IBS.
- Benchmarking of theory accomplished.

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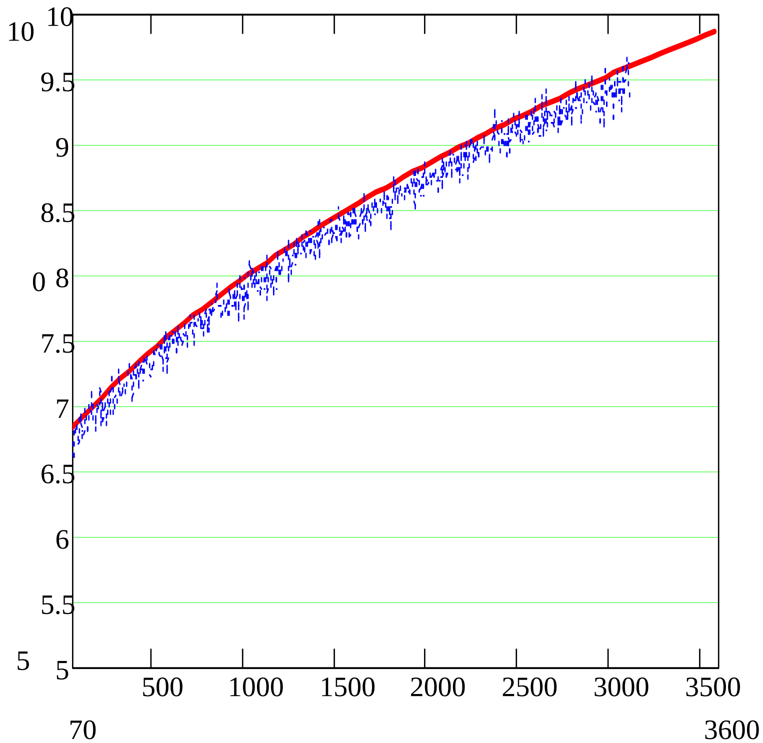
RHIC IBS experiment (2005)

Measured both planes, both rings, fully coupled Good agreement to theory, but over limited time span

Bunch length

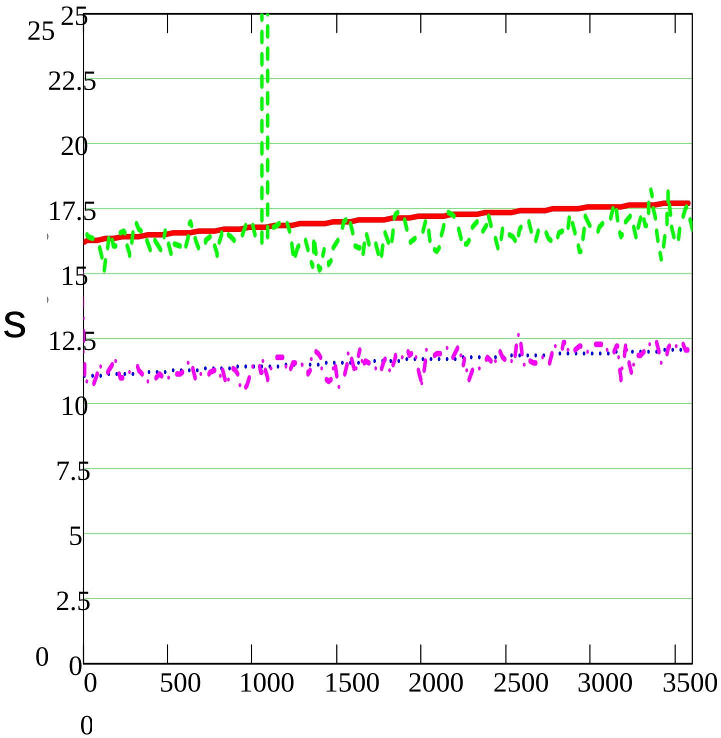
FWHM ns



time [sec]

Emittance x and y

95% Norm. microns



time [sec]

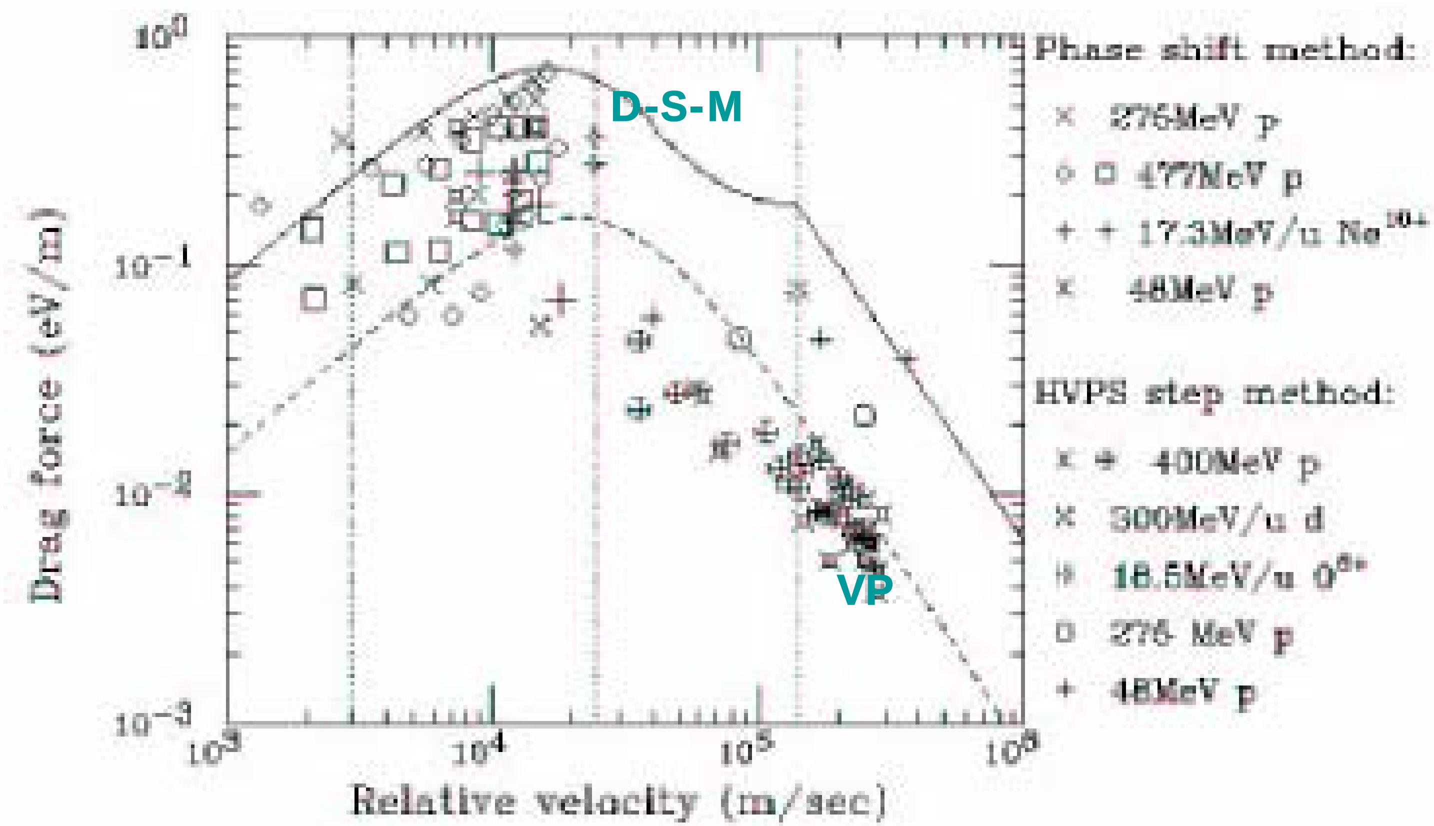
VORPAL code (Tech-X, Colorado): Simulate the friction in binary collisions

Early 2002 initiated SBIR with Tech-X. Goals:

- Obtain accurate friction and diffusion coefficients
  - Resolve discrepancies in analytical theory
  - Determine validity of Z^2 scaling
  - Understand effects of space charge on friction
  - Understand the effects of magnetization
    - from weak to strong
    - effect of field errors
  - What happens at small Coulomb log, 1 ~ 2
  - Provide table of coefficients for dynamic codes

Uncertainty in the experimental and theoretical scene

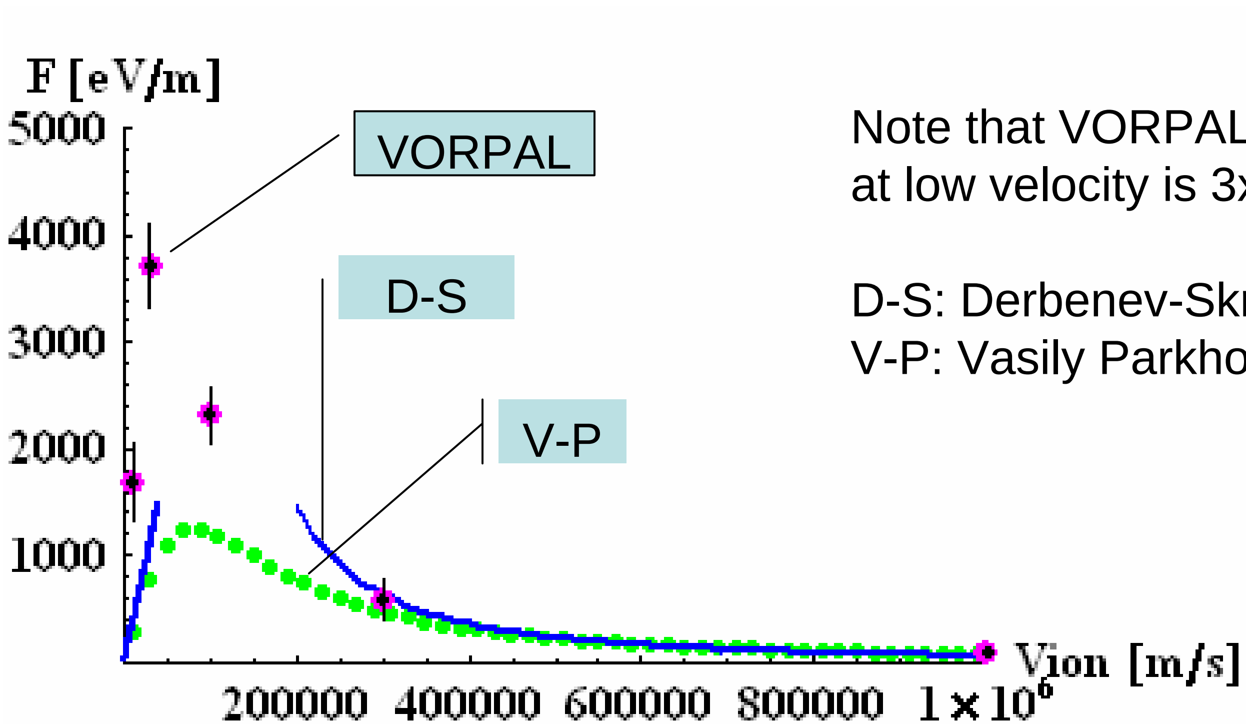
Y-N. Rao et al.: CELSIUS, Sweden'2001, longitudinal friction:



VORPAL's Friction force, RHIC parameters

very good magnetization: B=5T; $T_{e,tr}$=400 eV, $V_{ion,\ trans}$=0

Drag force



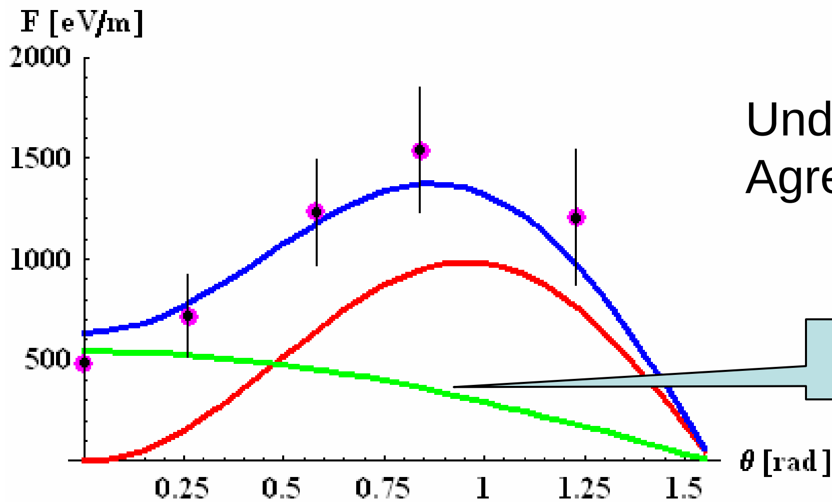
Ion velocity

Note that VORPAL slope at low velocity is 3x theory.

D-S: Derbenev-Skrinsky analytic
V-P: Vasily Parkhomchuk empiric

VORPAL guidance

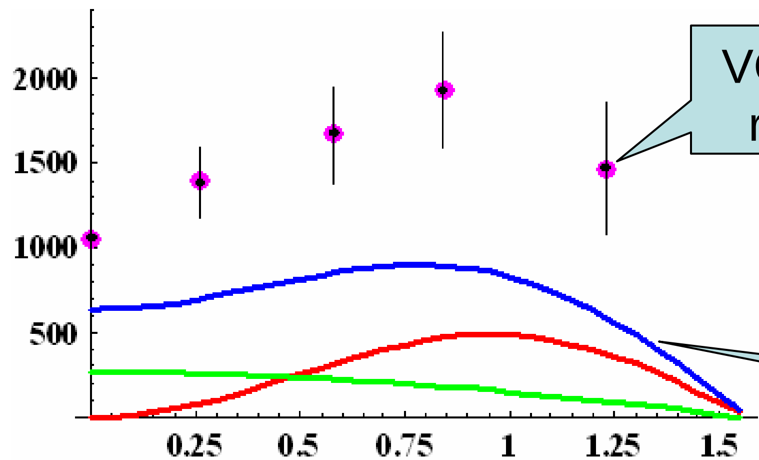
Drag force



Under good magnetization:
Agreement with D-S

V-P

Drag force



VORPAL results

Under poor magnetization:
Goes beyond theory's reach

D-S

Ion angle relative to solenoid field, radians

Summary - VORPAL

- Limited benchmarking of analytic formulae for magnetized cooling made
- Simulations of RHIC parameters started
- Benchmarking with experiments started
- The code is powerful, break-through results, objectives will be met.

Cooling dynamics codes

- Collaborations put in place with BINP Novosibirsk in 2000 and JINR Dubna in 2001.
- We got the cooling dynamics codes SimCool from BINP and BetaCool from JINR.
- Years of development spent to evolve the codes to RHIC needs and gain confidence, including benchmarking between the two codes.
- Many physics effects/models were added or improved and benchmarked.

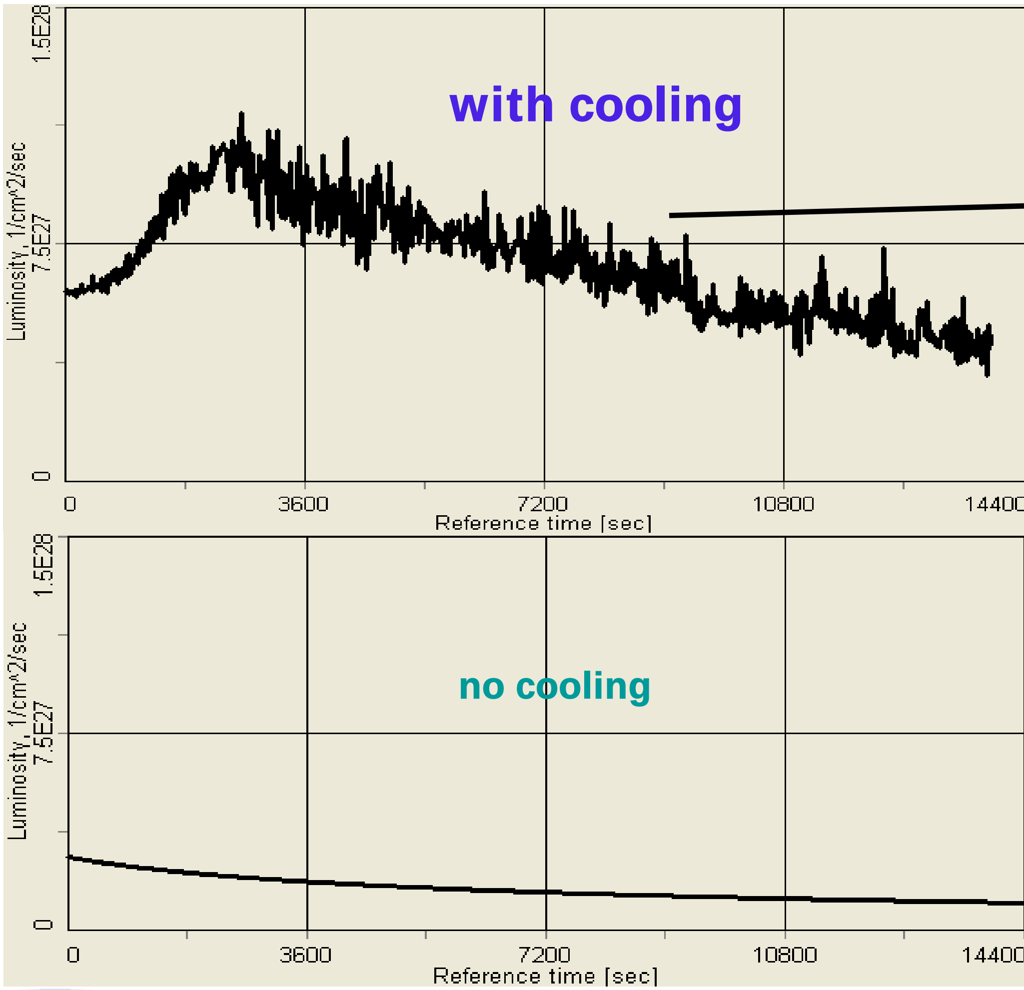
IBS models in dynamic codes benchmarked and extended

- Accurate models of IBS for Gaussian distributions implemented & benchmarked in the JINR BetaCool code:
  - Martini's model
  - Bjorken-Mtigwa model
- IBS models under cooling: still to be benchmarked:
  - Detailed (by Burov)
  - Core-tail (Fedotov et al.)
  - Bi-Gaussian (by Parzen)

BetaCool: Luminosity with / without magnetized cooling, Au 100 GeV/A

Lumi-
nosity

Lumi-
nosity



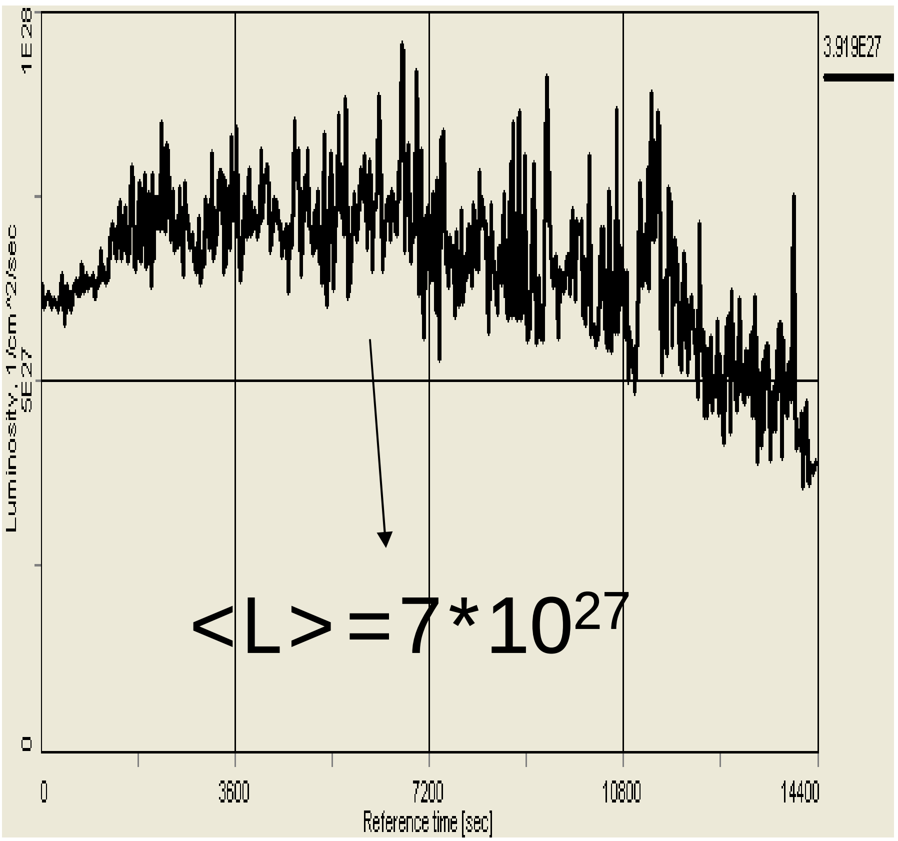
$<L> = 7 * 10^{27}$

E-cooling: factor of 10 increase in average luminosity per store

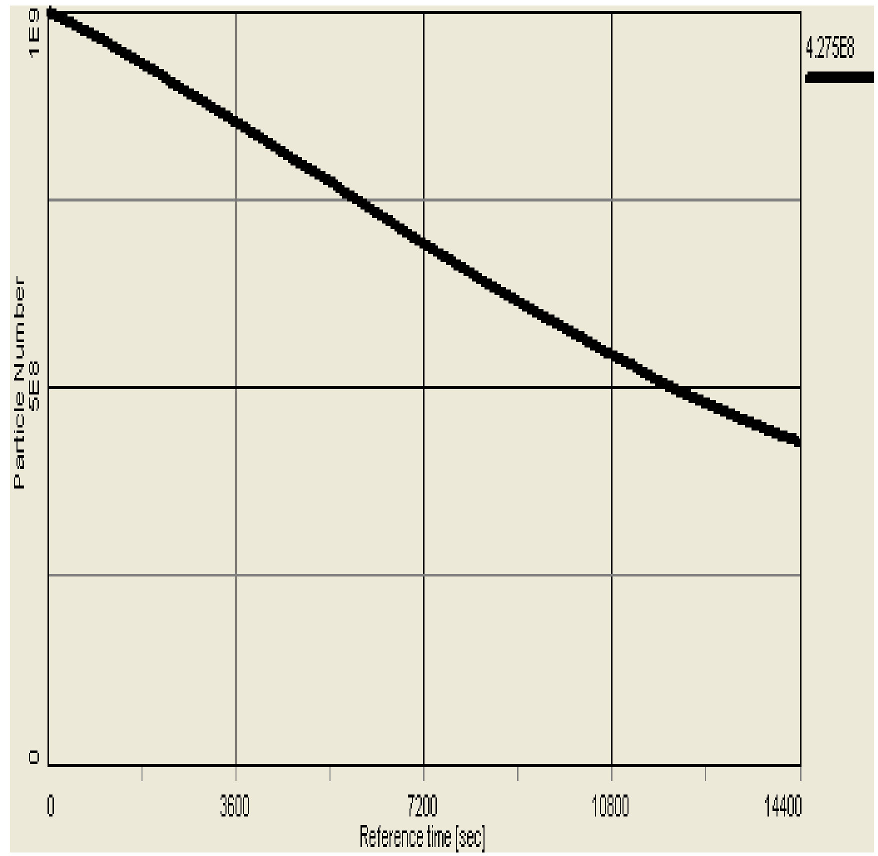
Time into store (seconds)

Non-magnetized cooling, with $Q=5nC$, $\varepsilon_N=3\mu m$, $\sigma_e=4.5mm$

Luminosity, increased x10



Number of particles in bunch



Time into store (seconds)

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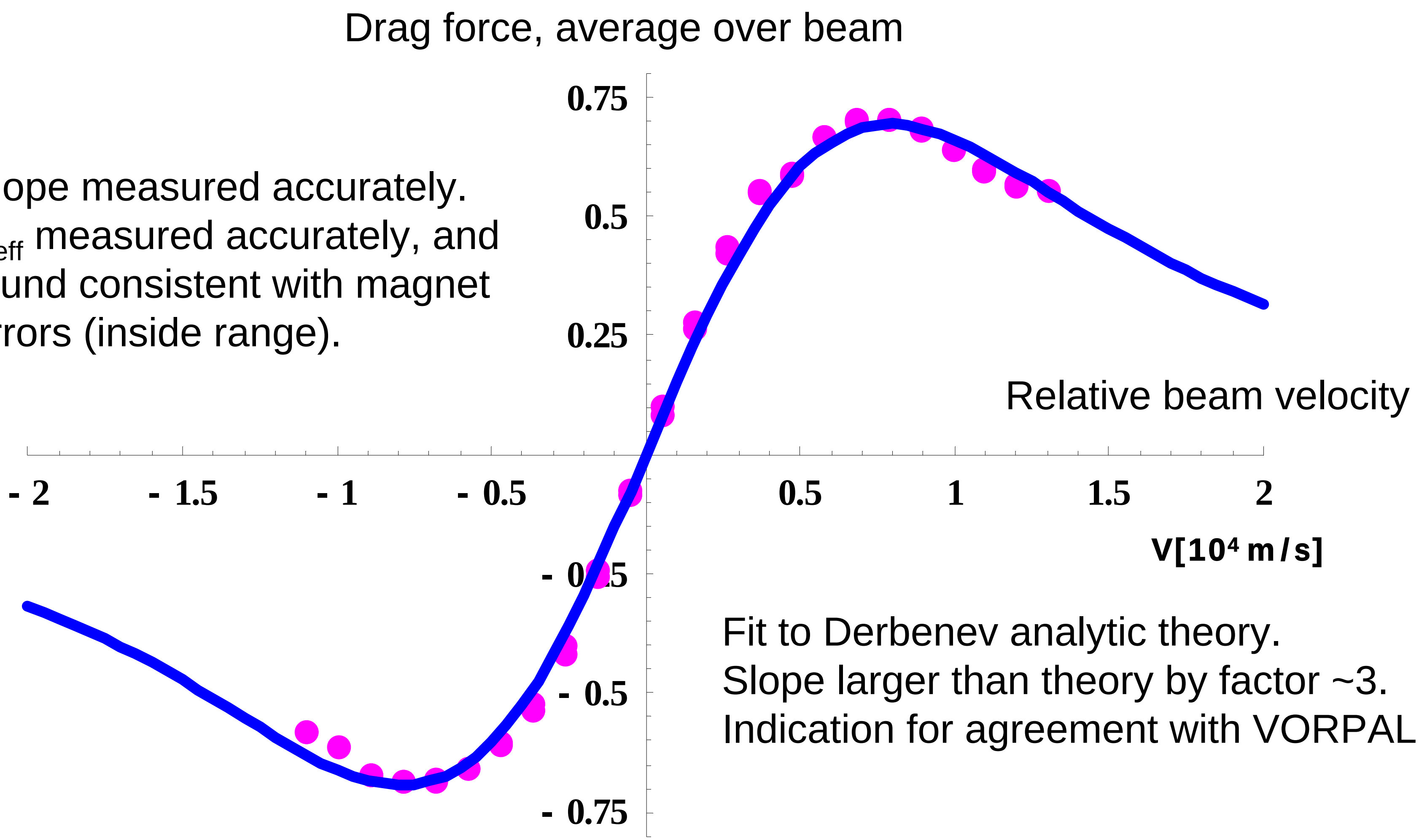
Beam experiments towards high-energy electron cooling

Beam experiments on low-energy coolers:

- Accurate measurement of cooling force and code benchmarking.
- Benchmark new models of IBS required to treat accurately a distribution shrinking under cooling.
- Create conditions expected in High Energy Cooler and study
  - magnetized cooling with small Coulomb logarithm
  - effect of solenoid errors
- Two runs produced a wealth of results.

Fitting V_{eff} from basic principles, March 5 data: B=0.12T, I_e=300mA

Slope measured accurately.
V_{eff} measured accurately, and found consistent with magnet errors (inside range).



Fit to Derbenev analytic theory.
Slope larger than theory by factor ~3.
Indication for agreement with VORPAL.

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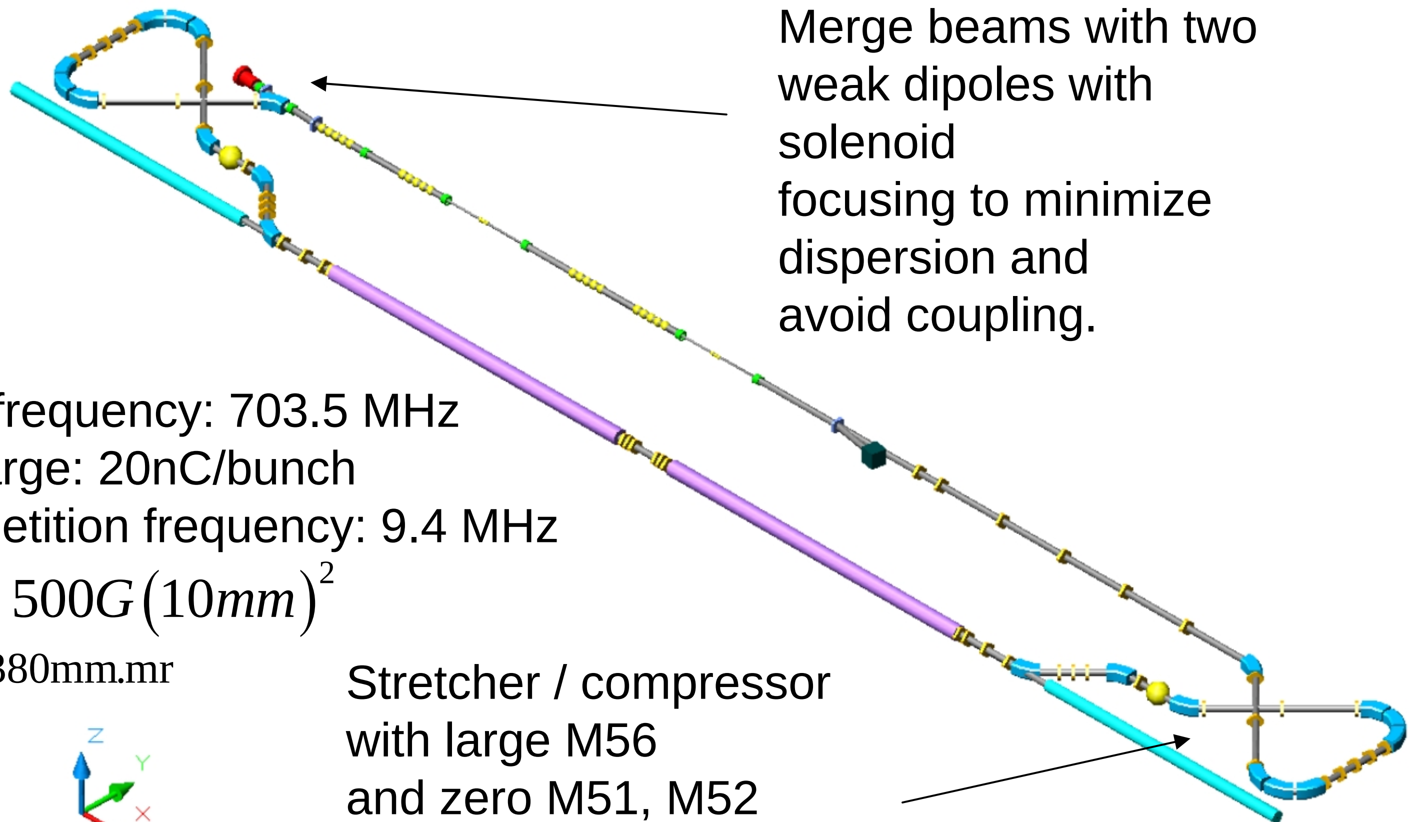
Schematic Layout of Magnetized Cooler



Merge beams with two weak dipoles with solenoid focusing to minimize dispersion and avoid coupling.

RF frequency: 703.5 MHz
Charge: 20nC/bunch
Repetition frequency: 9.4 MHz

$$B_S \sigma_S^2 = 500G\left(10mm\right)^2$$

$\mathcal{M} \sim 380\text{mm.mr}$

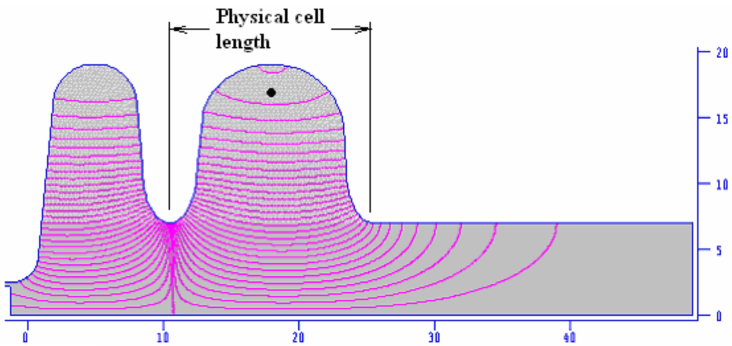
Stretcher / compressor with large M56 and zero M51, M52

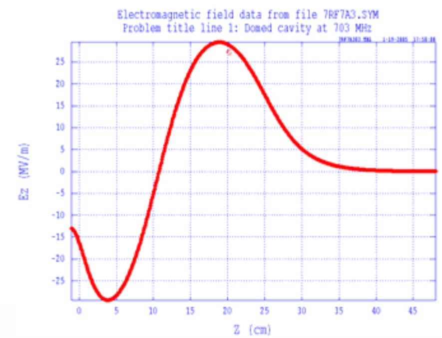
Use two solenoids with opposing fields to eliminate coupling in the ion beam.
A quadrupole matching section between the solenoids maintains magnetization.

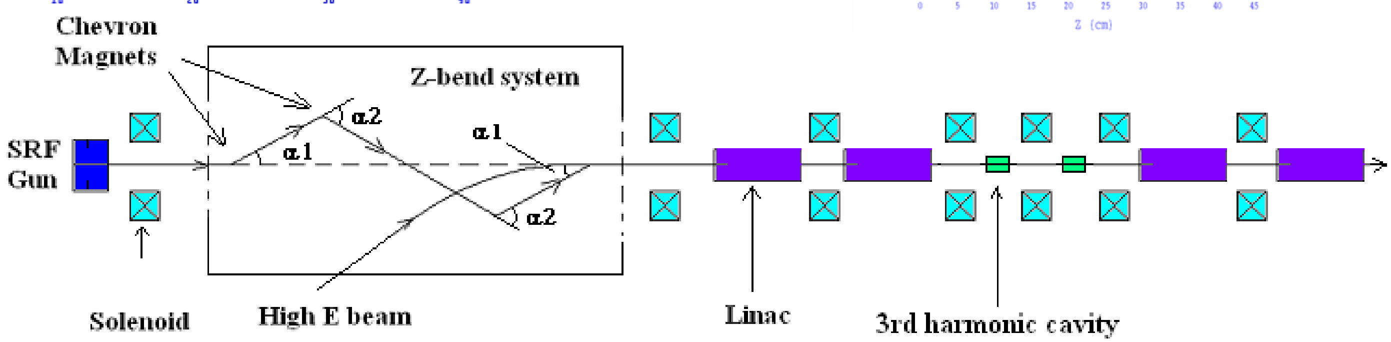
The electron machine R&D

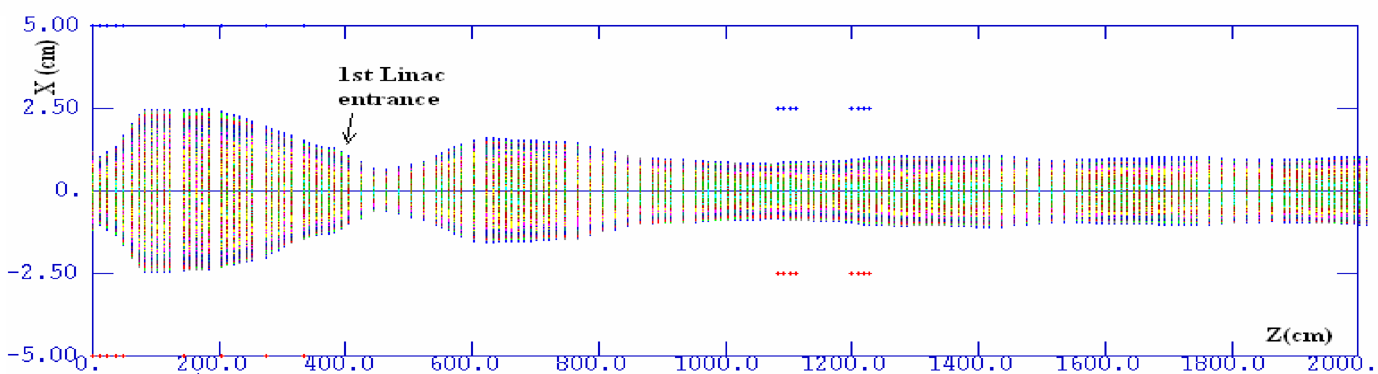
- Beam dynamics
- Photocathodes, including diamond amplified photocathodes
- Superconducting RF gun
- Energy Recovery Linac (ERL) cavity
- ERL demonstration

Gun and ERL


Physical cell length
0
10
20
30
40
0
5
10
15
20

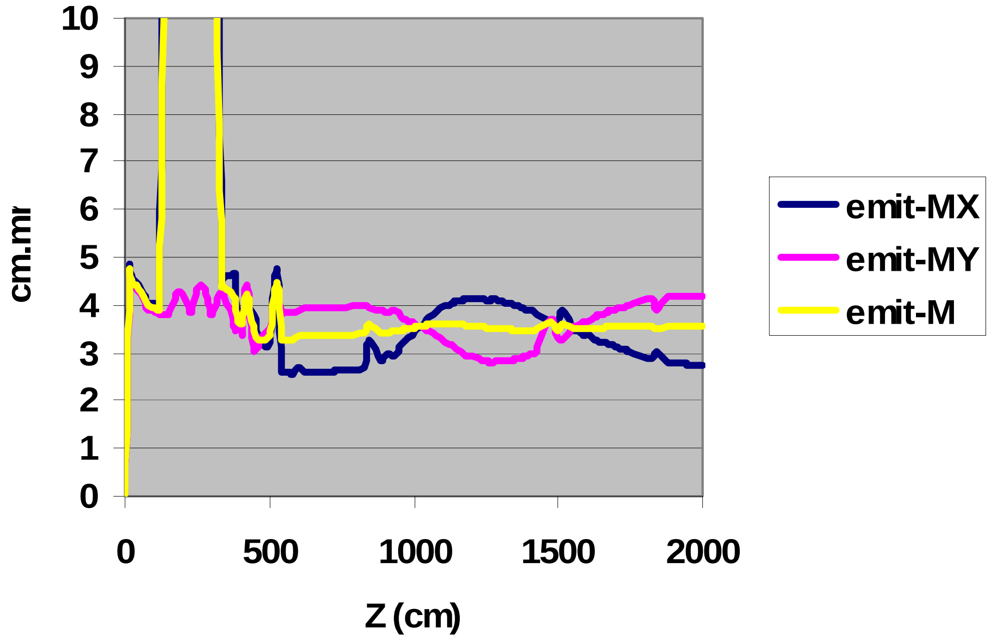

Electromagnetic field data from file 7RF7A3.SYM
Problem title line 1: Domed cavity at 703 MHz
Ez (MV/m)
Z (cm)


Chevron Magnets
Z-bend system
SRF Gun
α2
α1
α1
α2
Solenoid
High E beam
Linac
3rd harmonic cavity

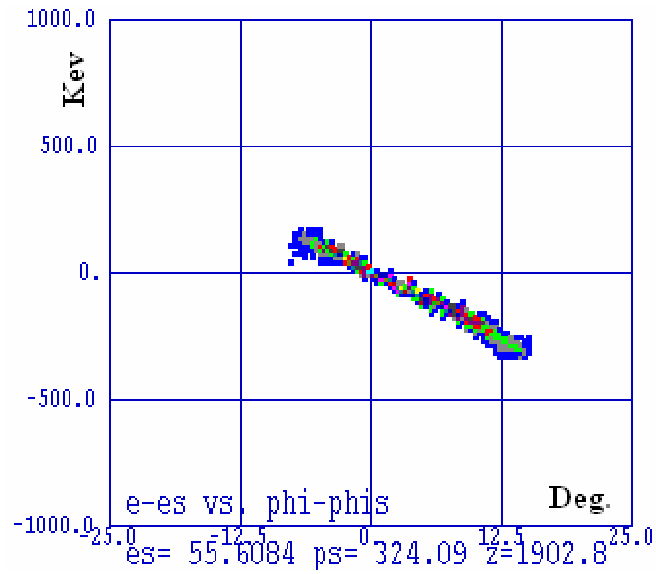

X (cm)
5.00
2.50
0.
-2.50
-5.00
1st Linac entrance
Z(cm)
0.
200.0
400.0
600.0
800.0
1000.0
1200.0
1400.0
1600.0
1800.0
2000.0

Emittance, 20 nC, magnetized, at end of linac

Transverse emittance vs. position



Longitudinal phase space



Final transverse emittance (rms, normalized) is about 35μ. Following multi-variable optimization, 28μ.

Longitudinal emittance at linac's exit is 100deg.keV

R&D ERL under construction

To study the issues of high-brightness, high-current electron beams as needed for RHIC II and eRHIC.

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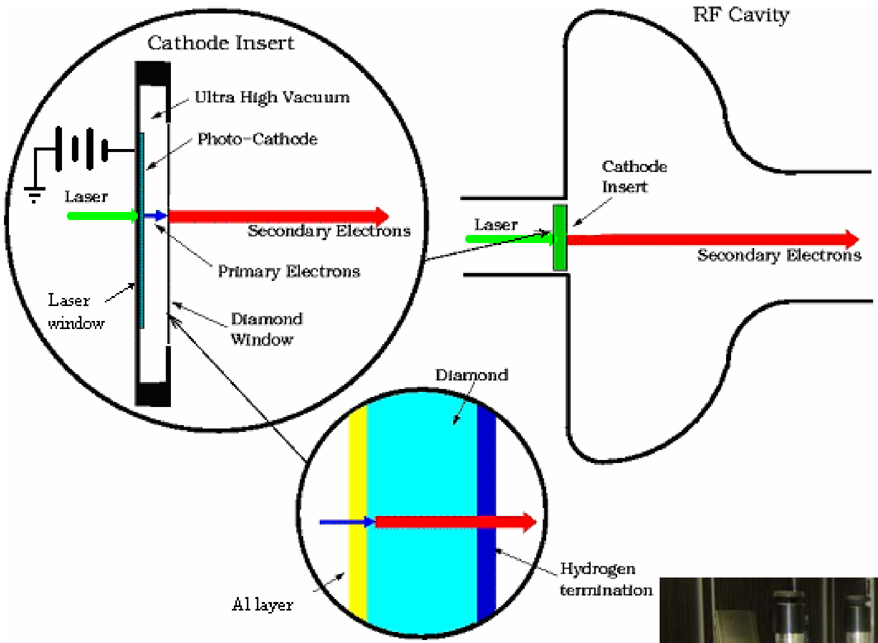
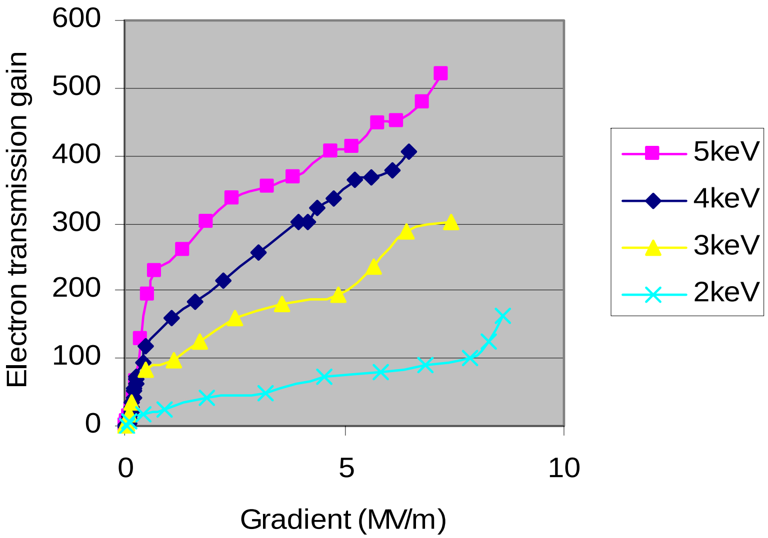
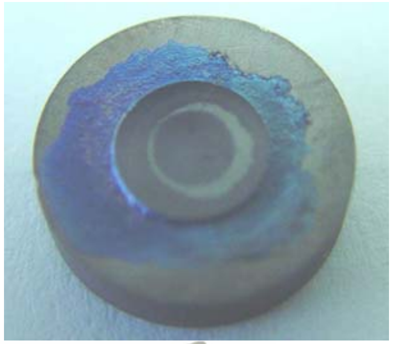
BNL ERL original developments

Diamond amplified photocathode





Photocathode fabrication chamber



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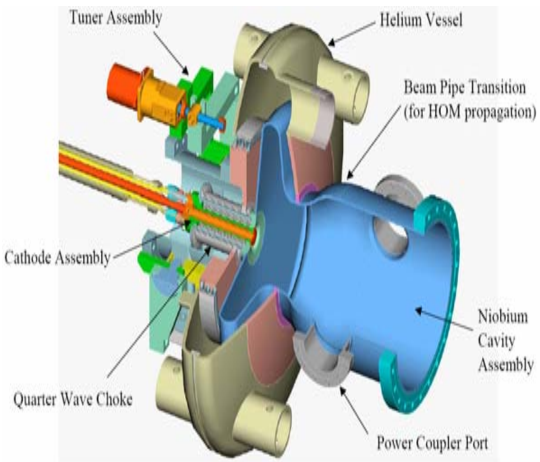
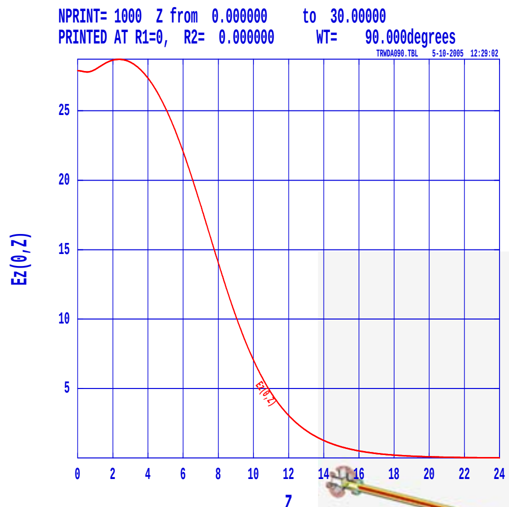
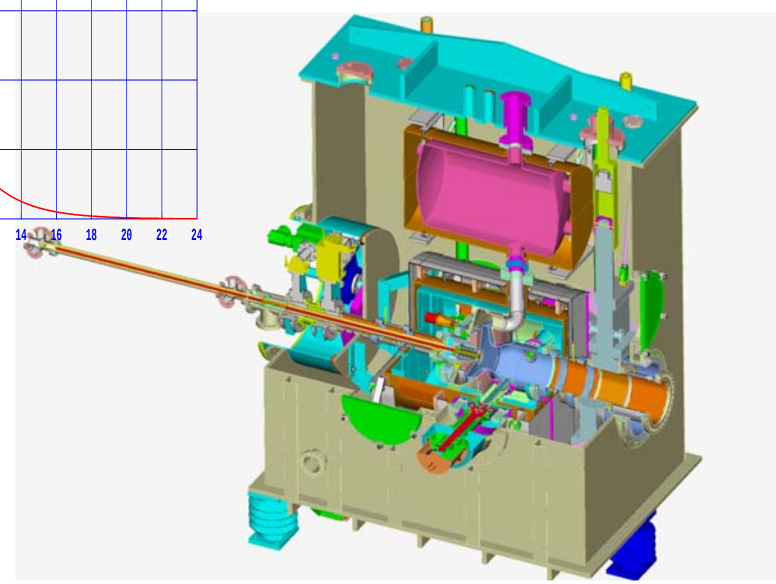
BNL ERL original developments

Ampere-class superconducting RF gun







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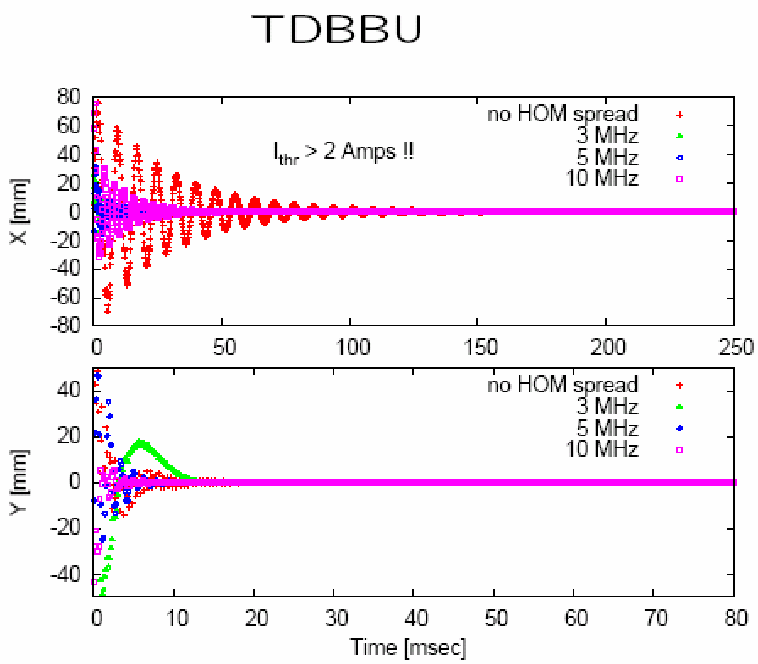
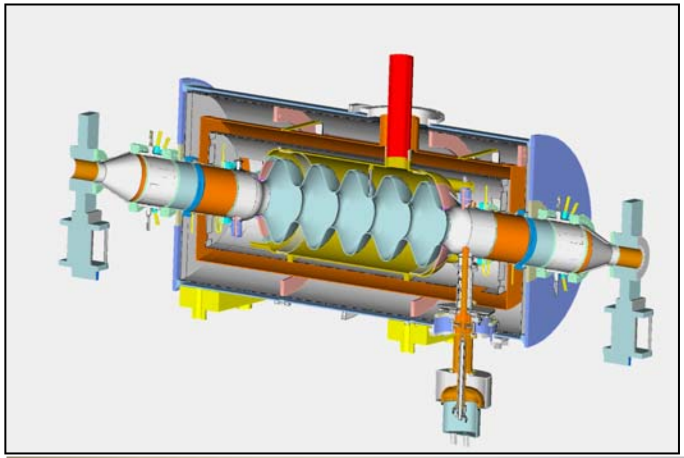
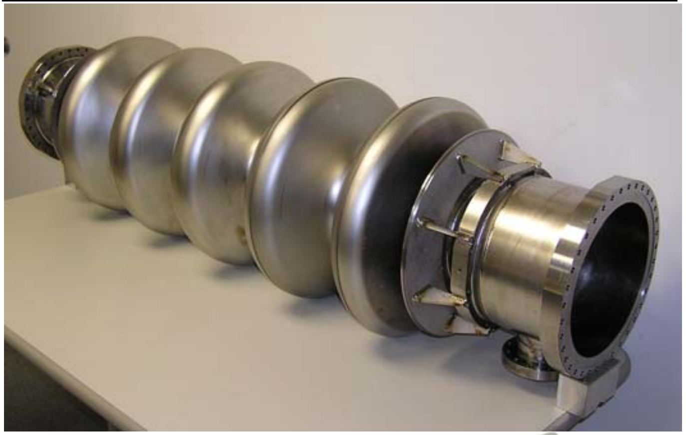
BNL ERL original developments

SRF ERL cavity for ampere-class current.







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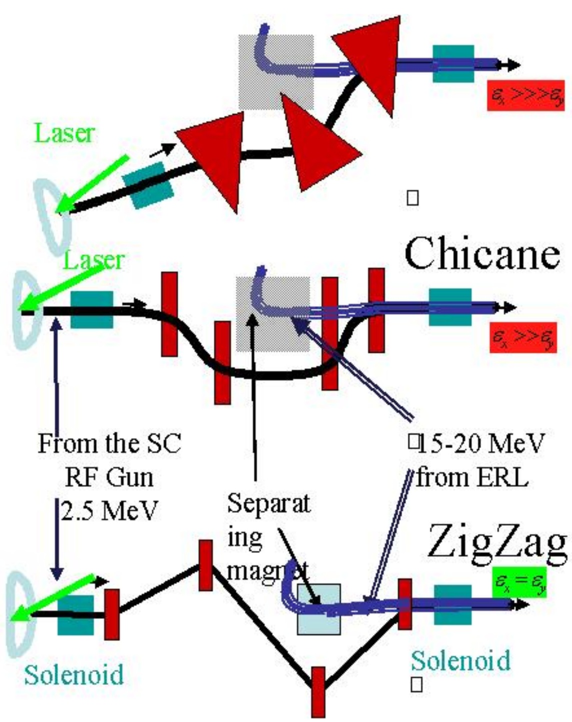
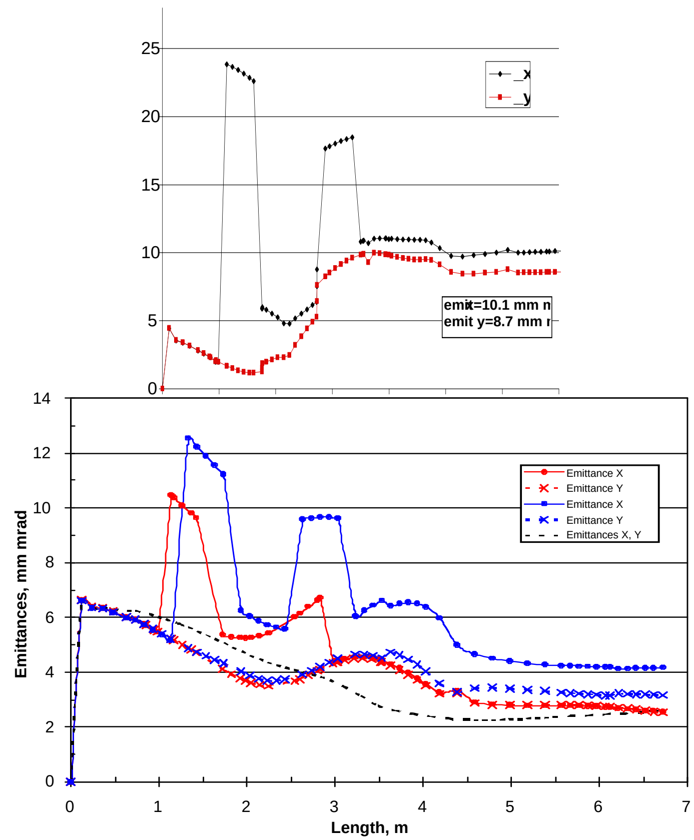
BNL ERL original developments

Merging optics for ERL at high-charge





Sources of Funding, k$

	FY03	FY04	FY05	FY06 (Exp./Req.)
DOE	900	2000	2000	2000/3000
BNL Prog. Dev/GPP	600	1200	1200	600
SBIR Tech-X	100	850	850	
SBIR AES			100	750
JTO Cryo-module	350	300	100	
ONR Photo-cathode		533		600
JTO ERL			500	500
Navy Photoinjector			600	1000
Total	1950	4883	5350	5450

Significant saving and a better R&D program are made possible by utilizing diverse resources.

ERL Material Funding Plan

in $K

2.0	ERL	Material & Services	Cumulative through FY05	FY06	FY07	FY08
2.1	Superconducting R.F.Cavity	1714	1714	0	0	0
2.2	RF Systems	4165	2280	1539	347	0
2.3	Injector Systems	2637	744	1393	500	0
2.4	Cryogenics Systems	508	382	126	0	0
2.5	Vacuum Systems	717	0	577	140	0
2.6	Magnet Systems	340	0	170	170	0
2.7	Magnet Electrical Systems	551	0	551	0	0
2.8	Electron Beam Dump Systems	241	0	0	241	0
2.9	Beam Instrumentation	534	5	0	530	0
2.10	Control Systems	343	0	0	0	343
2.11	Solenoid	1067	0	0	0	1067
2.12	Conventional Facilities	290	290	0	0	0
2.13	Safety Systems	81	81	0	0	0
2.14	E-Cooling Installation	257	60	64	133	0
2.15	Project Services	518	156	150	133	79
	Total Project	13963	5713	4569	2192	1489

E Cooling Labor Effort

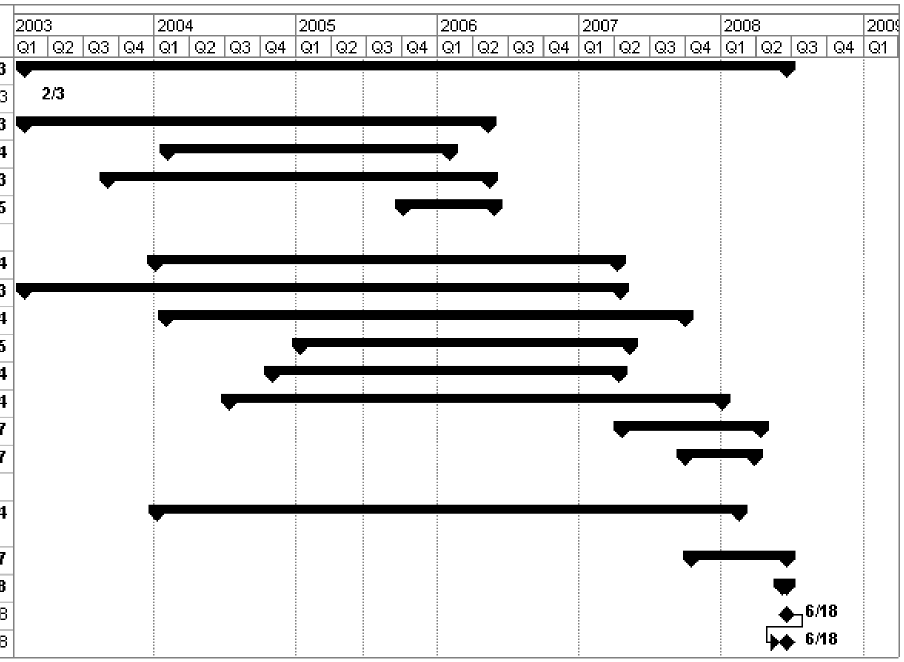
(FTE's)

	FY04	FY05
• Electron Cooling Group	5.1	6.8
• Other (matrix)	1.0	2.9

Timeline – funding driven.

Need front loaded distribution to complete nearly 1 year earlier.

ID	Task Name	Duration	Start
1	**e-CX / ERL Project**	**1349 days**	**Mon 2/3/03**
2	Project Start	0 days	Mon 2/3/03
3	**Develop & Procure the SC 5-cell RF cavity**	**822 days**	**Mon 2/3/03**
59	**5-Cell Cavity Preparation & String Assembly**	**501 days**	**Wed 2/4/04**
225	**Cavity Mechanical Installation**	**673 days**	**Thu 9/4/03**
295	**Assemble SRf Cavity & Associated Components**	**160 days**	**Thu 10/6/05**
303			
304	**SC Electron Gun Procurement**	**817 days**	**Mon 1/5/04**
356	**Photocathode System Development & Procurement**	**1056 days**	**Mon 2/3/03**
370	**Assemble & Test of Rf Gun & Associated Systems**	**918 days**	**Mon 2/2/04**
399	**Design & Procurement of RF Gun to Dump Vacuum System**	**583 days**	**Mon 1/10/05**
408	**Beam Dump Procurement**	**609 days**	**Mon 11/1/04**
419	**Beam Instrumentation - Develop, Design & Procure**	**867 days**	**Mon 7/12/04**
430	**Gun-to-Cavity-to-Dump Controls**	**243 days**	**Fri 4/20/07**
454	**Assemble Photocathode, Rf Gun, Cavity & Beam Dump for test**	**122 days**	**Mon 10/1/07**
464			
465	**Dev., Design & Procurement of ERL Magnets, PSs, Controls & Vacuum System**	**1026 days**	**Thu 1/8/04**
545	**ERL Installation , All Systems**	**169 days**	**Mon 10/15/07**
566	**Systems Integration Complete**	**10 days**	**Wed 6/4/08**
570	System Run & Testing Begins	0 days	Wed 6/18/08
571	Project Complete	0 days	Wed 6/18/08



Summary

- A vigorous and sweeping R&D program was initiated a few years ago and is making good progress.
- Our theory, simulation and benchmarking experiments are close to providing us with a precise set of requirements for electron cooling of RHIC.
- Our electron beam dynamic simulations show that we should be able to generate the required beam.
- Progress made on experimental program to demonstrate the critical electron beam generating components.
- We conclude that our luminosity increase goal for RHIC-II (factor of 10) can be achieved.
- Moving $1M from FY'08 to FY'06 will save the program about one year.